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Measurements of *CP* Violation and Mixing in Charm Decays at LHCb

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During run I, the LHCb experiment at the LHC, CERN, collected 1.0 fb^{-1} of pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$ and 2.0 fb^{-1} at $\sqrt{s} = 8\,\mathrm{TeV}$, yielding the world's largest sample of decays of charmed hadrons. This sample is used to search for direct and indirect *CP* violation in charm and to measure D^0 mixing parameters. Recent measurements from several complementary decay modes are presented.

1 Introduction

The LHCb detector is a forward-arm spectrometer, with pseudo-rapidity coverage $2 < \eta < 5$, specifically designed for high precision measurements of decays of b and c hadrons [1]. During run I, the experiment collected 1.0 fb^{-1} of pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$ and 2.0 fb^{-1} at $\sqrt{s} = 8\,\mathrm{TeV}$, yielding the world's largest sample of decays of charmed hadrons. This allows *CP* violation and mixing in charm to be studied with unprecedented precision in many complementary decay modes. The Standard Model (SM) predicts *CP* asymmetries to be $\mathcal{O}(10^{-3})$ or less in charm interactions [2, 3]; observation of significantly larger *CP* violating effects could indicate new physics.

For a decay $\mathrm{D} \to f$ and its *CP* conjugate $\bar{\mathrm{D}} \to \bar{f}$, with amplitudes A_f and $\bar{A}_{\bar{f}}$ respectively, direct *CP* violation is quantified by $A_d = (|A_f|^2 - |\bar{A}_{\bar{f}}|^2)/(|A_f|^2 + |\bar{A}_{\bar{f}}|^2)$. For D^0 mesons, the mass eigenstates $|\mathrm{D}_{1,2}\rangle$, with masses $m_{1,2}$ and widths $\Gamma_{1,2}$, are defined in terms of the flavour eigenstates, $|\mathrm{D}^0\rangle$ and $|\overline{\mathrm{D}}^0\rangle$, as $|\mathrm{D}_{1,2}\rangle = p|\mathrm{D}^0\rangle \pm q|\overline{\mathrm{D}}^0\rangle$, with p and q complex, satisfying $|p|^2 + |q|^2 = 1$. The rate of mixing is quantified by $x \equiv 2(m_2 - m_1)/(\Gamma_1 + \Gamma_2)$ and $y \equiv (\Gamma_2 - \Gamma_1)/(\Gamma_1 + \Gamma_2)$. *CP* violation in mixing is quantified by $A_m \equiv (|q/p|^2 - |p/q|^2)/(|q/p|^2 + |p/q|^2)$ and the interference between mixing and decay (when $f = \bar{f}$) by $\lambda_f \equiv q\bar{A}_f/pA_f = |q\bar{A}_f/pA_f|\, e^{i\phi}$.

The flavour of the D^0 meson at production is determined using either $\mathrm{D}^{*+} \to \mathrm{D}^0\pi_s^+$ decays, where the charge of the "soft pion", π_s, track gives the D^0 flavour, or $\mathrm{B} \to \mathrm{D}^0\mu^- X$ decays, where the charge of the μ track gives the D^0 flavour.

2 Multi-body D decays

Multi-body D decays are sensitive to *CP* violation due to the interference of different resonances across the multi-body phase space. In $\mathrm{D}^0 \to \mathrm{K}^+\mathrm{K}^-\pi^+\pi^-$ decays, triple products of final state particle momenta in the D^0 rest frame, defined as $C_T \equiv \vec{p}_{\mathrm{K}^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})$ and

$\bar{C}_T \equiv \vec{p}_{K^-} \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+})$ for D^0 and $\overline{D}^0$ mesons respectively, are odd under T. The decay rate asymmetries

$$A_T \equiv (\Gamma(C_T > 0) - \Gamma(C_T < 0))/(\Gamma(C_T > 0) + \Gamma(C_T < 0)),$$
$$\bar{A}_T \equiv (\Gamma(-\bar{C}_T > 0) - \Gamma(-\bar{C}_T < 0))/(\Gamma(-\bar{C}_T > 0) + \Gamma(-\bar{C}_T < 0)),$$

are thus sensitive to *CP* violation. However, final state interactions introduce significant asymmetries, and so the difference $a_{CP}^{T\text{-odd}} \equiv \frac{1}{2}(A_T - \bar{A}_T)$ is used to access the asymmetry of the D^0 meson. The observable $a_{CP}^{T\text{-odd}}$ is by definition insensitive to production and detection asymmetries, so is very robust against systematic uncertainties.

Using 3 fb^{-1} of data, the phase space integrated measurements are found to be [4]

$$\begin{aligned} A_T &= (-7.18 \pm 0.41(\text{stat}) \pm 0.13(\text{syst}))\%, \\ \bar{A}_T &= (-7.55 \pm 0.41(\text{stat}) \pm 0.12(\text{syst}))\%, \\ a_{CP}^{T\text{-odd}} &= (0.18 \pm 0.29(\text{stat}) \pm 0.04(\text{syst}))\%. \end{aligned}$$

This shows no evidence of *CP* violation but achieves a significant improvement in precision over the previous world average of $a_{CP}^{T\text{-odd}} = (0.11 \pm 0.67)$[5].

The same measurements are also performed in 32 bins of Cabibbo-Maksimowicz phase space variables, defined as the invariant mass squared of the $\pi^+\pi^-$ (K^+K^-) pair, $m^2_{\pi^+\pi^-}$ ($m^2_{K^+K^-}$); the cosine of the angle of the π^+ (K^+) with respect to the direction opposite to the D^0 momentum in the $\pi^+\pi^-$ (K^+K^-) rest frame, $\cos(\theta_\pi)$ ($\cos(\theta_K)$); and the angle between the K^+K^- and $\pi^+\pi^-$ planes in the D^0 rest frame, ϕ. The asymmetries are extracted in each bin of phase space and $a_{CP}^{T\text{-odd}}$ calculated. A χ^2 test for consistency across the phase space is performed, yielding a p-value of 74 %. Similarly, binning in the decay time of the D^0 candidates and performing the same test gives sensitivity to indirect *CP* violation. This yields a p-value of 72 %, so there is no evidence for direct or indirect *CP* violation.

A complementary method for studying *CP* violation in multi-body D meson decays is to examine *CP* asymmetries across the multi-body phase space directly. Signal yields are obtained in bins of the multi-body phase space, and the test statistic $S^i_{CP} \equiv (N_i(D^0) - \alpha N_i(\overline{D}^0))/\sqrt{\alpha(N_i(D^0) + N_i(\overline{D}^0))}$, calculated in each bin i, where $\alpha \equiv N(D^0)/N(\overline{D}^0)$ cancels any global production and detection asymmetries. A χ^2 test for consistency with zero *CP* violation is performed using $\chi^2 = \Sigma_i {S^i_{CP}}^2$ and $N_{bins} - 1$ degrees of freedom. This analysis has been performed on $D^0 \to K^+K^-\pi^+\pi^-$ and $D^0 \to \pi^+\pi^-\pi^+\pi^-$ candidates, using 1 fb^{-1} of data, for which the nominal binning scheme yields a p-value of 9.1 % (41 %) for $D^0 \to K^+K^-\pi^+\pi^-$ ($D^0 \to \pi^+\pi^-\pi^+\pi^-$) [6]. The decay $D^+ \to \pi^-\pi^+\pi^+$ has also been studied in this way, using 1 fb^{-1} of data [7]. Various binning schema are used, as well as an unbinned method to measure *CP* asymmetries, all of which yield p-values of more than 20 %. Thus, no evidence for *CP* violation is found in these decay modes.

3 *CP* violation in $D^\pm_{(s)} \to K^0_S h^\pm$

The singly-Cabibbo-suppressed (SCS) decays $D^\pm \to K^0_S K^\pm$ and $D^\pm_s \to K^0_S \pi^\pm$ offer a means of measuring direct *CP* violation with high precision. The *CP* asymmetry is defined as

$\mathcal{A}_{CP}^{D_{(s)}^{\pm}\to K_S^0 h^{\pm}} \equiv (\Gamma(D_{(s)}^{+}\to K_S^0 h^+) - \Gamma(D_{(s)}^{-}\to K_S^0 h^-))/(\Gamma(D_{(s)}^{+}\to K_S^0 h^+) + \Gamma(D_{(s)}^{-}\to K_S^0 h^-))$, while the measured asymmetry is

$$\begin{aligned}\mathcal{A}_{\rm meas}^{D_{(s)}^{\pm}\to K_S^0 h^{\pm}} &\equiv (N_{\rm sig}^{D_{(s)}^{+}\to K_S^0 h^{+}} - N_{\rm sig}^{D_{(s)}^{-}\to K_S^0 h^{-}})/(N_{\rm sig}^{D_{(s)}^{+}\to K_S^0 h^{+}} + N_{\rm sig}^{D_{(s)}^{-}\to K_S^0 h^{-}}) \\ &\simeq \mathcal{A}_{CP}^{D_{(s)}^{\pm}\to K_S^0 h^{\pm}} + \mathcal{A}_{\rm prod}^{D_{(s)}^{\pm}} + \mathcal{A}_{\rm det}^{h^{\pm}} + \mathcal{A}_{K_S^0}.\end{aligned}$$

Here $N_{\rm sig}$ is the number of signal candidates of the given decay, $\mathcal{A}_{\rm prod}^{D_{(s)}^{\pm}}$ is the production asymmetry of the $D_{(s)}^{\pm}$ meson, $\mathcal{A}_{\rm det}^{h^{\pm}}$ is the detection asymmetry of the $h^{\pm}$ meson, and $\mathcal{A}_{K_S^0}$ is the combined detection and *CP* asymmetry of the K_S^0 meson. Assuming negligible *CP* violation in the Cabibbo-favoured (CF) decays $D_s^{\pm}\to K_S^0 K^{\pm}$, $D^{\pm}\to K_S^0\pi^{\pm}$ and $D_s^{\pm}\to \phi\pi^{\pm}$, the production and detection asymmetries cancel in the double difference

$$\begin{aligned}\mathcal{A}_{CP}^{DD} &\equiv \left[\mathcal{A}_{\rm meas}^{D_s^{\pm}\to K_S^0\pi^{\pm}} - \mathcal{A}_{\rm meas}^{D_s^{\pm}\to K_S^0 K^{\pm}}\right] - \left[\mathcal{A}_{\rm meas}^{D^{\pm}\to K_S^0\pi^{\pm}} - \mathcal{A}_{\rm meas}^{D^{\pm}\to K_S^0 K^{\pm}}\right] - 2\mathcal{A}_{K_S^0}, \\ &= \mathcal{A}_{CP}^{D^{\pm}\to K_S^0 K^{\pm}} + \mathcal{A}_{CP}^{D_s^{\pm}\to K_S^0\pi^{\pm}},\end{aligned}$$

while the K_S^0 asymmetry is calculable, so the sum of the *CP* asymmetries can be measured. Similarly the individual *CP* asymmetries can be accessed using

$$\begin{aligned}\mathcal{A}_{CP}^{D^{\pm}\to K_S^0 K^{\pm}} &= \left[\mathcal{A}_{\rm meas}^{D^{\pm}\to K_S^0 K^{\pm}} - \mathcal{A}_{\rm meas}^{D_s^{\pm}\to K_S^0 K^{\pm}}\right] - \left[\mathcal{A}_{\rm meas}^{D^{\pm}\to K_S^0\pi^{\pm}} - \mathcal{A}_{\rm meas}^{D_s^{\pm}\to \phi\pi^{\pm}}\right] - \mathcal{A}_{K_S^0}, \\ \mathcal{A}_{CP}^{D_s^{\pm}\to K_S^0\pi^{\pm}} &= \mathcal{A}_{\rm meas}^{D_s^{\pm}\to K_S^0\pi^{\pm}} - \mathcal{A}_{\rm meas}^{D_s^{\pm}\to \phi\pi^{\pm}} - \mathcal{A}_{K_S^0}.\end{aligned}$$

Using 3 $\rm fb^{-1}$ of data the results thus obtained are [8]

$$\begin{aligned}\mathcal{A}_{CP}^{D^{\pm}\to K_S^0 K^{\pm}} + \mathcal{A}_{CP}^{D_s^{\pm}\to K_S^0\pi^{\pm}} &= (+0.41 \pm 0.49({\rm stat}) \pm 0.26({\rm syst}))\%, \\ \mathcal{A}_{CP}^{D^{\pm}\to K_S^0 K^{\pm}} &= (+0.03 \pm 0.17({\rm stat}) \pm 0.14({\rm syst}))\%, \\ \mathcal{A}_{CP}^{D_s^{\pm}\to K_S^0\pi^{\pm}} &= (+0.38 \pm 0.46({\rm stat}) \pm 0.17({\rm syst}))\%.\end{aligned}$$

These are the most precise measurements of their kind to date and show no evidence of *CP* violation.

4 Mixing and *CP* violation in $D^0\to h^+h^{(\prime)-}$ decays

Decays of $D^0\to h^+h^{(\prime)-}$ provide a means of measuring direct and indirect *CP* violation, as well as mixing, in the D^0 system. The measured *CP* asymmetry in $D^0\to K^+K^-$ and $D^0\to\pi^+\pi^-$ decays, flavour tagged using $B\to D^0\mu^- X$ decays, is $\mathcal{A}_{\rm meas}^{D^0\to h^+h^-} = \mathcal{A}_{CP}^{D^0\to h^+h^-} + \mathcal{A}_{\rm det}^{\mu^{\pm}} + \mathcal{A}_{\rm prod}^{B}$. The $\pi^+\pi^-$ and K^+K^- final states are *CP* eigenstates, so have no detection asymmetry. Defining $\Delta\mathcal{A}_{CP} \equiv \mathcal{A}_{\rm meas}^{D^0\to K^+K^-} - \mathcal{A}_{\rm meas}^{D^0\to\pi^+\pi^-} = \mathcal{A}_{CP}^{D^0\to K^+K^-} - \mathcal{A}_{CP}^{D^0\to\pi^+\pi^-}$, the nuisance asymmetries cancel. Similarly to the analysis described in Sec. 3, CF decays can be used to cancel nuisance asymmetries as $\mathcal{A}_{CP}^{D^0\to K^+K^-} = \mathcal{A}_{\rm meas}^{D^0\to K^+K^-} - \mathcal{A}_{\rm meas}^{D^0\to K^-\pi^+} + \mathcal{A}_{\rm det}^{K^{\mp}\pi^{\pm}}$, and $\mathcal{A}_{\rm det}^{K^{\mp}\pi^{\pm}}$ can be calculated using the asymmetries of $D^+\to K^-\pi^+\pi^+$ and $D^+\to K_S^0\pi^+$ decays, and the known $\mathcal{A}_{K_S^0}$. The asymmetry $\mathcal{A}_{CP}^{D^0\to\pi^+\pi^-}$ can then be determined using $\mathcal{A}_{CP}^{D^0\to\pi^+\pi^-} = \mathcal{A}_{CP}^{D^0\to K^+K^-} - \Delta\mathcal{A}_{CP}$.

Using 3 fb^{-1} of data yields [9]

$$\begin{aligned}
\Delta\mathcal{A}_{CP} &= (+0.14 \pm 0.16(\text{stat}) \pm 0.08(\text{syst}))\%,\\
\mathcal{A}_{CP}^{\mathrm{D}^0\to\mathrm{K}^+\mathrm{K}^-} &= (-0.06 \pm 0.15(\text{stat}) \pm 0.10(\text{syst}))\%,\\
\mathcal{A}_{CP}^{\mathrm{D}^0\to\pi^+\pi^-} &= (-0.20 \pm 0.19(\text{stat}) \pm 0.10(\text{syst}))\%.
\end{aligned}$$

Indirect *CP* violation in $\mathrm{D}^0 \to \mathrm{K}^+\mathrm{K}^-$ and $\mathrm{D}^0 \to \pi^+\pi^-$ decays can be measured using

$$A_\Gamma \equiv \frac{\hat{\Gamma}(\mathrm{D}^0 \to f) - \hat{\Gamma}(\overline{\mathrm{D}}^0 \to f)}{\hat{\Gamma}(\mathrm{D}^0 \to f) + \hat{\Gamma}(\overline{\mathrm{D}}^0 \to f)} \approx \eta_{CP}\left[\frac{1}{2}(A_m + A_d)y\cos\phi - x\sin\phi\right].$$

Here, $\hat{\Gamma}$ is the inverse of the effective lifetime of the decay and η_{CP} is the *CP* eigenvalue of f. The effective lifetimes are measured directly using a data-driven, per-candidate correction for the selection efficiency on 1 fb^{-1} of data, yielding [10]

$$\begin{aligned}
A_\Gamma(\pi\pi) &= (+0.033 \pm 0.106(\text{stat}) \pm 0.014(\text{syst}))\%,\\
A_\Gamma(\mathrm{KK}) &= (-0.035 \pm 0.062(\text{stat}) \pm 0.012(\text{syst}))\%.
\end{aligned}$$

Thus, no evidence for direct or indirect *CP* violation in $\mathrm{D}^0 \to \mathrm{h}^+\mathrm{h}^-$ decays is found.

Mixing in the D^0 system is measured using the ratio of the decay rates of "wrong sign" DCS $\mathrm{D}^0 \to \mathrm{K}^+\pi^-$ to "right sign" CF $\mathrm{D}^0 \to \mathrm{K}^-\pi^+$ as a function of D^0 decay time, as

$$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} = R_D + \sqrt{R_D}y't + \frac{x'^2 + y'^2}{4}t^2,$$

where $R_D = \left|\frac{A_{DCS}}{A_{CF}}\right|^2$, $x' = x\cos(\delta) + y\sin(\delta)$, $y' = -x\sin(\delta) + y\cos(\delta)$, and $\delta = \arg\left(\frac{A_{DCS}}{A_{CF}}\right)$. Using 3 fb^{-1} of data yields [11]

$$x'^2 = (5.5 \pm 4.9) \times 10^{-5}, y' = (4.8 \pm 1.0) \times 10^{-3}, R_D = (3.568 \pm 0.066) \times 10^{-3}.$$

Allowing for *CP* violation yields:

$$A_D \equiv (R_D(\mathrm{D}^0) - R_D(\overline{\mathrm{D}}^0))/(R_D(\mathrm{D}^0) - R_D(\overline{\mathrm{D}}^0)) = (-0.7 \pm 1.9)\%,$$

$$0.75 < |q/p| < 1.24, (68.3\ \%\ \mathrm{CL}).$$

These are the most precise measurements of mixing in the D^0 system and of *CP* violation in $\mathrm{D}^0 \to \mathrm{K}^+\pi^-$ decays to date.

5 Conclusions

There is a rich programme of charm physics studies at the LHCb experiment, with many complementary measurements already performed using some or all the 3 fb^{-1} of data collected during run I. No evidence for *CP* violation has been found, though constraints of $\mathcal{O}(10^{-3})$ have been achieved in many decay modes. Mixing in the D^0 system has also been measured to unprecedented precision. With run II shortly to begin, and the LHCb upgrade in the near future, there are great prospects for future measurements with precisions of $\mathcal{O}(10^{-4})$, which will tightly constrain, or potentially discover, new physics.

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